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The equivalent resistance and power requirements of electric fishing electrodes

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Abstract The empirical relationship between different sizes of electric fishing anodes, water conductivity and equivalent resistance was modelled for a range of electric fishing ring anode designs currently in use. In addition, equivalent resistance values were measured for several cathode designs. Knowledge of the equivalent electrode resistance allowed determination of the input power required to energise an electric fishing system for a range of water conductivities, circuit voltages and electrical waveforms. The values of equivalent electrode resistance did not correspond well with values obtained from previously published theoretical methods for calculating equivalent electrode resistance.

KEYWORDS: electric fishing, electrofishing, electrode resistance, power requirements.

Introduction

Knowledge of the electrical resistance of the electrode system used in electric fishing is both fundamental to understanding the electrical characteristics of the circuit voltage that is apportioned to the different electrodes and vital if it is required to determine the power required to energise the electrodes.

Within an electric fishing circuit the voltage applied to the circuit is divided proportionally at each electrode in proportion to the resistance ratio of the electrodes. A low resistance cathode and a high resistance anode will therefore result in a higher anode voltage and thus a larger electric field from the anode. Knowledge of this factor is important if excessively high voltage gradients are to be avoided (at either anode or cathode) and for efficient use of available circuit voltage and generator power.

With the exception of very high conductivity water ($> 1000\ \mu\text{S cm}^{-1}$), available power from the generator is rarely an issue when using pulsed direct current (PDC) waveforms. However, concerns regarding the potential for fish injury caused by using PDC has led to a general recommendation that direct current (DC) should be used wherever possible (Beaumont, Taylor, Lee & Welton 2002; Snyder 2003). However, large anode diameters and/or high conductivity water plus the use of high-applied voltages when fishing with DC can result in overloading of generators. Knowledge of the required power input for the electrode array for the target water conductivity will overcome this potentially hazardous situation.

When a volume of water separates two electrodes, the electrical resistance between the electrode connectors is a function of two components. One component is the sum of the two individual electrode resistances (i.e. the electrical resistance of the metal from which the electrodes are constructed), the other, and major component, is a function of the ambient conductivity of the water, the spacing of the electrodes, and the dimensions and geometry of the electrodes. Novotny & Priegel (1974) described a theoretical relationship between these parameters to evaluate the Electrode Equivalent Resistance for a range of electrode shapes (sphere, ring, cylinder and flat plate) according to:

$$R = f(\gamma)/K\sigma_{\mathrm{w}} \qquad (1)$$

where,

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$$\gamma = t/d \quad (2)$$

and, for a circular or ring shaped electrode made from round or tube shaped material, t is the diameter (gauge) of ring material (mm), d the ring diameter (mm), σ_w the ambient water conductivity (μS cm^{-1}), K the principal electrode dimension (for a ring = diameter), and $f(\gamma)$ is ascertained from a graph of electrode resistance factors for different electrode shapes.

Kolz, Reynolds, Temple, Boardman & Lam (1998) also discussed ways of calculating the equivalent resistance of electrodes; but used ring circumference for the parameter t in Eqn 2. In addition, Kolz (1993) gave some empirical equivalent resistance values for differing electrode shapes but values for only two diameters of ring electrode are given, thus limiting the extrapolation of the data to other diameters of ring electrodes. It is also not clear whether water conductivity values are ambient or specific values, thus further limiting extrapolation of the information to other situations.

The above theoretical calculations are cumbersome, however, and Kolz *et al.* (1998) recommended measuring the equivalent resistance of the electrodes rather than using the theoretical calculations. Where standard ring shaped electrodes of unknown electrical resistance are used, however, a simple method of ascertaining their resistance would be useful for determining circuit resistance and thus power required to energise the electrode system in differing water conductivities. This paper determines the empirical relationship between different sizes of electric fishing anodes, water conductivity and equivalent resistance for a range of electric fishing ring anode designs currently in use, as a basis for setting optimal input power required to energise an electric fishing system for a range of water conductivities, circuit voltages and electrical waveforms.

Methods

Electrode designs representing anode (ring shaped) and cathode (braid and mesh plates) shapes commonly used in UK electric fishing operations were constructed and their equivalent electrical resistance measured empirically. Ring electrodes were of a range of diameters and gauges (thickness of the metal making the ring) (Table 1). Examples of anode ring designs used by UK manufacturers of electric fishing control box equipment were also tested. Cathode types included three different lengths of copper braid, and differing designs and sizes of flat mesh. The equivalent resistance of a solid metal plate was also assessed (Table 2).

The electrodes were suspended in water (a natural millstream) from a non-conductive cradle that allowed almost uninhibited contact of the electrode with the water. Channel width of the millstream was uniform but slight variation in depth and bottom conductivity may have been present. The equivalent resistance of the anodes was measured by applying a known low voltage DC potential across a pair of identical electrodes and measuring the circuit current (one electrode thus becoming the anode and the other the cathode). Electrodes were periodically agitated to prevent the build up of gas bubbles (from electrolytic action) on the electrode surfaces affecting the resistance characteristics. Measurements were taken both with the anode suspended at the water surface and at a depth of 500 mm (water depth was about 1500 mm). Flow in the stream was negligible. These two depths were chosen to represent the highest resistance value that could be generated (at the surface) and the usual maximum operating depth of hand-held anodes (thus the minimum resistance and maximum power values that were likely to be encountered).

For reasons of safety, most of the electrical measurements were carried out using a bank of four 12 V 33 Ah sealed lead acid batteries, connected in series to give a nominal supply voltage of 48 V DC. By undertaking tests at low voltage, the electric shock hazards associated with this work were virtually eliminated. As the effects being measured were linear with reference to the applied voltage, values obtained could be scaled up to any given voltage. To verify this, a limited number of tests were carried out using an Intelisys FMII bankside fishing system (Intelisys Ltd,

Table 1. Anode sizes evaluated and equivalent resistance measured at 350 μS cm^{-1} ambient conductivity

Anode size (mm)		
Diameter (mm)	Gauge (mm)	Measured resistance (Ω)
400	6	28
100	6	73
200	6	47
600	6	22
400	10	27
200	10	44
600	10	21
400	20	25
600	20	19
290*	6	24
325*	12	30
380†	15	27

*Manufacturers design (stainless steel).
†Manufacturers design (copper).

Manchester, UK) powered by a 1-kVA Honda generator to give a high voltage (150–300 V DC) source.

Electrical coupling between the electrodes (which would affect electrical current between the electrodes and thus the calculated resistance values) was assessed by positioning two, 600-mm diameter ring electrodes 8 m apart in the stream and energising them with ~48 V DC. Voltage gradient between them was measured using a 'penny probe' (Beaumont *et al.* 2002) with 100 mm separation between contacts.

Cathode resistance was measured using similar methodology to that used to measure the anode resistance. Measurements were taken at the water surface and with the cathode resting on the streambed (as per usual electric fishing practice); only the latter data are presented here.

Specific water conductivity was measured using a laboratory calibrated Ciba-Corning Checkmate no. 90 conductivity meter. During the periods when the measurements were taken specific conductivity averaged 535 μS cm^{-1}, temperature averaged 6.4 °C, from this ambient conductivity was calculated to be approximately 350 μS cm^{-1} from

$$C_{a(t)} = C_S/[1.023^{(25-t)}] \tag{3}$$

where $C_{a(t)}$ is ambient conductivity at temperature t and C_s the specific conductivity (corrected to 25 °C) (Mackereth, Heron & Talling 1978).

From the voltage and current readings the effective electrode resistance was calculated

$$2R_{\mathrm{ref}} = V/I \tag{4}$$

where R_{ref} is reference electrode resistance (Ohms), V voltage (volts) and I current (Amps). Thereafter single electrodes of differing diameter and thickness were substituted for one of the reference electrodes and the effective resistance of the new electrode calculated as

$$R_x = (V/I) - R_{\mathrm{ref}} \tag{5}$$

where R_x is the resistance of the new electrode (Ohms).

These relationships were used to construct a model of physical electrode characteristics and equivalent resistance for ring anodes. This empirical model for anode resistance was evaluated against the theoretical model of electrode resistance for ring-shaped electrodes described by Novotny & Priegel (1974). Using the electrode resistance it is possible to calculate the power needed to energise the electrodes for a range of voltage values (Eqn 5).

$$Power(\mathrm{Watts}) = V^2/R \tag{6}$$

where V is Circuit voltage (volts) and R the circuit resistance (Ohms).

As an electrode's equivalent resistance varies with water conductivity, if measured for a particular value of water conductivity and then used in water having a different conductivity, the electrode's equivalent resistance will change in inverse proportion (Eqn 7) to the two values of water conductivity (Kolz 1993).

$$[R_2/R_1] = [c_1/c_2] \tag{7}$$

where, R_1 is the resistance (Ohms) of the electrode in the water having a conductivity equal to c_1 and R_2 the resistance of the electrode in the water having a conductivity of c_2. The resistance of an electrode can be calculated for any value of water conductivity once its resistance is experimentally determined for water of known conductivity using:

$$R_2 = (R_1 \times c_1)/c_2 \tag{8}$$

From Eqn 8, the equivalent resistance of differing electrodes can be used to calculate the power required

Table 2. Cathode sizes evaluated and equivalent resistance measured at 350 μS cm^{-1} ambient conductivity

Dimension 1 (mm)	Dimension 2 (mm)	Cathode type	Braid thickness/mesh size (mm)	Measured resistance (Ω)
750	25	Copper braid	3	48
1500	25	Copper braid	3	31
3000	25	Copper braid	3	20
250	250	Steel mesh	13	49
500	500	Steel mesh	13	27
500	500	Stainless steel perforated sheet	6	21
750	750	Steel mesh	13	19
600	550	Expanded aluminium mesh	1 inch	26
290	390	Perforated aluminium mesh		35
290	400	Steel weldmesh	1 inch	34
300	410	2 mm Thick aluminium plate		34
160	170	Perforated aluminium mesh		60
170	170	Steel weldmesh	1 inch	64

to energise the electrodes at differing water conductivities using Eqn 6.

To produce the power in the water (Watts) from the DC waveform, an AC generator must power an inverter to convert the AC waveform to a DC waveform. This inverter presents a non-linear load to the (AC) generator hence the issue of adverse Power Factor (PF) needs be taken into account in order to calculate the generator size required to power the system. The PF of an electric fishing control box will depend upon the circuitry within the unit (Cividino 1992). Adverse PF occurs in AC input power converters of the type used in electric fishing control boxes because of the non-linear nature of the rectifier/capacitor input circuit. This results in an input current with a high harmonic content. These harmonic components do not contribute to the power as they do not have corresponding components in the input voltage waveform and in practice, with currently available equipment, the PF may be as low as 0.6. This value was used in the calculations of Input VA required to energise the electrodes.

Results

The linear voltage gradient between the two 600-mm ring electrodes shows some asymmetry and a minimum around the halfway position between the two electrodes (Fig. 1). A low gradient plateau was not present.

The effect on the electrode resistance of differing gauges (thicknesses) of ring was evaluated. Although higher resistances were found with smaller gauge material, differences were small with the maximum difference for any anode tested being 7 Ω (15%) between the 6- and 20-mm gauge, 200-mm diameter rings. On average, 10-mm gauge rings were 6% less resistive than 6-mm gauge, and 20-mm gauge 9% less than 10 mm (Fig. 2).

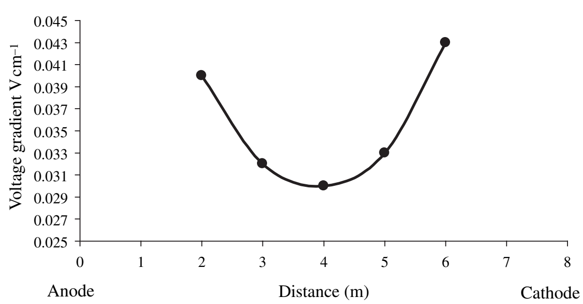

Figure 1. Inter-electrode voltage gradient between two 600 mm rings. Anode positioned at 0 m and cathode at 8 m. Applied voltage −49.2 V.

As gauge of ring material had minimal effect on the readings, data for all ring electrodes were combined and results of the resistance readings stratified into those taken at the water surface and those taken at 500 mm depth. Equivalent electrode resistance was higher when measured at the surface compared with the 500-mm depth measurements (Fig. 3); measurements at 500 mm depth being on average 70% of those measured at the surface.

Equivalent electrode resistance for ring electrodes consisted of a power law relationship with electrode diameter. For an electrode at the surface:

$$R_{eq} = 3076D^{-0.74}r^2 = 0.93; P \leq 0.001 \tag{9}$$

where, R_{eq} is the equivalent resistance of the ring anode (Ohms) and D the ring diameter (mm). For an electrode at 500 mm depth:

$$R_{eq} = 1956D^{-0.72}r^2 = 0.98; P \leq 0.001 \tag{10}$$

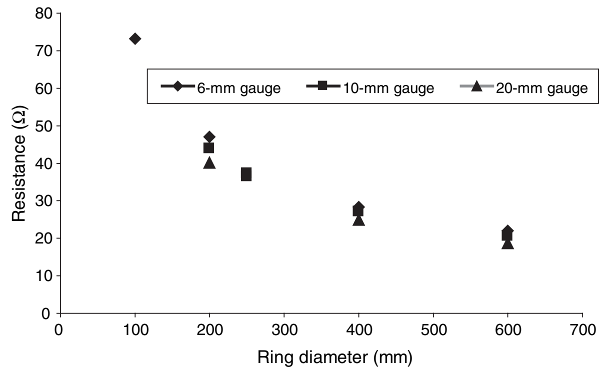

Figure 2. Equivalent resistance values for different gauges of ring electrode.

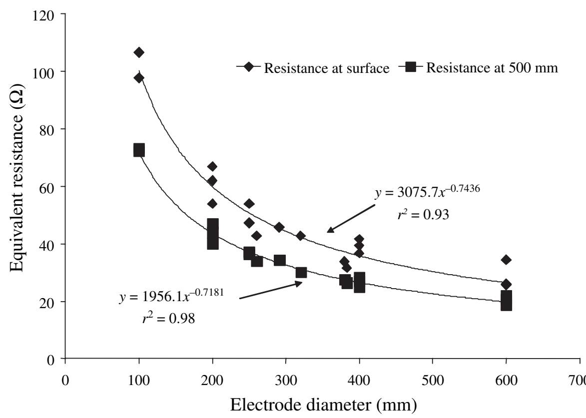

Figure 3. Relationship between ring diameter and equivalent resistance measured at surface and at 500 mm depth.

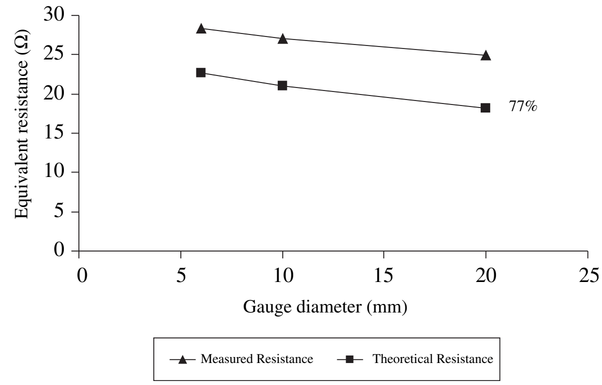

Figure 4. Comparison of measured and calculated resistance values for 400 mm ring anode.

Eqns 9 and 10 can be used to calculate the equivalent electrical resistance of any diameter of ring electrode and then adjusted according to the conductivity of the water in which it is being used using Eqn 8.

Measured values of resistance (at 500 mm depth) were compared with values calculated by the method proposed by Novotny & Priegel (1974). Figure 4 shows both these values for a 400-mm ring electrode calculated from Novotny & Priegel (1974) were on average 77% of the values measured in this study (Fig. 4).

Equivalent resistance values of the cathode designs (Table 2) indicated a wide range of equivalent resistance values. Cuinat (1967) stated that as the size of a mesh cathode is doubled the resistance will be halved. In this study the equivalent resistance of the mesh cathodes broadly agreed with this rule. The resistance of the braid cathodes, however, became approximately one-third less resistive for doubling the braid length.

The mesh cathodes had a lower resistance per unit area (area taken as the size covered by the mesh) than the braid design (area taken as length × width × thickness); this enables a smaller area of mesh material to achieve a given resistance.

Values for the ~300-mm × ~400-mm mesh designs and the solid plate very similar, suggesting the mesh conferred no electrical advantage.

Because of the varying sizes and designs of cathode it was not possible to model equivalent resistance values against the physical properties of the cathodes.

Resistance values of electrodes at differing water conductivities were used to construct graphs of the input power (VA) required to energise different electrode configurations for differing values of DC circuit voltage. Figure 5 shows data for an anode size of 400 mm diameter × 10 mm gauge (using a 1500 mm copper braid as the cathode).

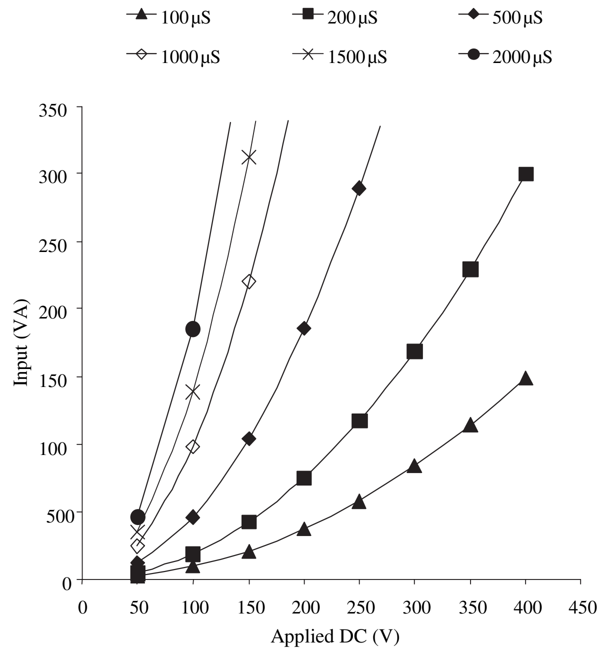

Figure 5. Input VA required to energise a 400-mm × 10-mm ring anode (plus 1500 mm braid cathode) at different water conductivity values (100–2000 μS) with a DC waveform.

If using pulsed DC waveforms, input VA is proportional to the duty cycle being used. Input VA required for pulsed DC waveforms can therefore be calculated. The relationship between required input VA, circuit voltage, electrode diameter, water conductivity and duty cycle was modelled for ring shaped anodes and according to:

$$\text{Input VA} = (V^2/R_a + R_c) \times (1/(PF \times 100)) \times DC \quad (11)$$

For a water depth of 500 mm

$$R_a = (((1956.1 \times (D^{-0.72})) \times 350)/C_w \quad (12)$$

and

$$R_c = (Cr \times 350)/C_w \quad (13)$$

where, V is the applied circuit voltage (volts), R_a anode resistance (Ohms), R_c cathode resistance (Ohms), DC percentage duty cycle (if PDC is used), C_w is the ambient conductivity of the water (μS cm^{-1}), Cr cathode resistance at 350 μS cm^{-1} (from Table 2) and PF the adverse Power Factor ratio (0.6). Eqns 11–13 can be entered into a computer spreadsheet (including portable machines for field use) where, when input variables are entered, the input VA for both DC and PDC output can be calculated. The relationships above can be extrapolated to twin anode situations by using circuit theory calculations for resistors in parallel.

$$R_{eq} = R_1 \times R_2 / R_1 + R_2 \tag{14}$$

where, R_{eq} is the circuit resistance, R_1 the equivalent resistance of electrode 1 and R_2 the equivalent resistance of electrode 2. Note that this relationship can be used to calculate resistance of both twin anodes and cathodes. Actual empirical measurements of twin electrodes in parallel circuits resulted in measurements slightly lower (~10%) than those predicted by circuit theory.

Discussion

In an ideal situation, when measuring equivalent electrical resistance of electrodes the electrodes would be far enough apart that inter-electrode coupling did not take place, thus affecting the readings taken. The 8-m separation between electrodes chosen in this study lies in the zone of 10–20 radii that Smith (1989) (in Snyder 1992) considered that (for ring electrodes) the electric field, although still being present, should, theoretically, be at a minimum. At these distances voltage gradient between two identical electrodes should be symmetrical and have at least two values on the minima. Some asymmetry in values did occur with the largest (600-mm diameter) electrodes used (possibly because of local variations in river bed conductivity) and a low gradient plateau was not present. If some inter-electrode coupling were taking place this would also have had an effect on the current readings when measuring the equivalent resistance values of the large electrodes (Beaumont *et al.* 2002), thus distorting the resistance calculations. No such effect was apparent indicating the effect of any electrode coupling was minimal.

Anode gauge thickness had very little impact upon electrode resistance; when compared with 10 mm gauge rings, 6 mm gauge were about 6% higher and 20 mm gauge 9% lower. However, there was some effect of depth on the measured resistance. Novotny & Priegel (1974) recommended doubling the equivalent resistance of an electrode measured at the surface to correct for surface effect. At the two depths used in this study, the deeper measurements were only 70% of the surface measurements. This discrepancy was expected, however, since Novotny and Priegel's data referred to electrodes only being half submerged whereas in this work the surface measurements were taken with the electrodes completely submerged. Data from the 500-mm depth readings were used in the subsequent extrapolations as they more realistically represented the depth at which an anode is held during electric fishing and because they provide a worse case scenario for determining power requirements (the lower the equivalent electrode resistance the more power is required).

The Novotny & Priegel (1974) theoretical values were on average 77% of the measured values. As stated above, Novotny & Priegel (1974) also considered the effects of shallow water operation on the resistance values of the electrodes, considering that their values are those for electrodes far removed from boundaries (water surface and bottom) and that a surface correction factor of two should be used to correct for the increase in resistance experienced by an electrode at the surface. When this correction factor was applied to the data, results were still considerably distant from the measured data.

This study showed that the variation of equivalent electrode resistance with ring diameter could be described by a power law equation ($P \leq 0.001$). The application of a simple conductivity correction to the relationship allows values to be obtained for any diameter of anode in any water conductivity.

Equivalent resistance per unit area for cathodes made from mesh was higher than for the braid. For situations where the cathode is trailed from a moving platform, the braid design is probably more ergonomic than the mesh design. Doubling the number of cathodes and wiring in parallel considerably reduced the total equivalent resistance of the cathodes.

The input power requirement for a 400-mm diameter anode (and 1500-mm braid cathode) at different applied DC voltages (Fig. 5) shows it is possible to ascertain the size generator required to power the electric fishing system (assuming a 0.6 PF conversion) at different input voltage values at a range of different water conductivities. Whilst Figure 5 shows power required when using DC, the percentage of the power being used by PDC can be determined by applying a correction to the DC data based on the percentage of the power (% duty cycle) being used compared with DC. In practical field use the values will vary about this value depending upon streambed conductivity variation and the proximity of the anode to the cathode (and in twin anode situations the proximity of the anodes to each other): values should therefore be regarded as a minimum. Figure 5 has been truncated at 7.5 kVA as this probably represents the maximum generator size (based on weight and physical size of generator) it is feasible to use in a field situation (and then only in boat-mounted situations). For practical purposes, where manual transportation is used, a

3 kVA generator (dry weight 60 kg) should probably be used as an upper limit for generator size.

Power input required to energise electric fishing gear using standard anode and cathode designs and DC waveform can be very high. If 3.0 kVA is the likely upper limit of generator size suitable for portable field use and 250 V input the likely minimum applied voltage required, a water conductivity of 500 μS is the probable upper limit for DC electric fishing (using a single 400-mm diameter anode and 1500-mm braid cathode).

This study elucidates equivalent electrode resistance values for a size range of electrode sizes and designs. Measurements were taken at depths representing the real-life situation of electric fishing, thus results are directly applicable to the types of classical electric fishing gears used. The results allow equivalent electrode resistance, and thus power requirements of electric fishing systems, to be calculated with a high degree of certainty without recourse to theoretical graphic extrapolations. This knowledge will allow workers to both assess generator size required for the water conductivity being fished and assess the anode:cathode resistance ratio to determine distribution of the circuit voltage between anode and cathode.

Acknowledgments

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